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# ON THE OUTER LIMIT FOR THE EXPANSION OF MAGNETIC BOTTLES EJECTED BY SOLAR PROTON FLARES

(NASA-TM-X-66243) ON THE OUTER LIMIT  
FOR THE EXPANSION OF MAGNETIC BOTTLES  
EJECTED BY SOLAR PROTON FLARES (NASA)

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ON THE OUTER LIMIT FOR THE EXPANSION OF MAGNETIC BOTTLES  
EJECTED BY SOLAR PROTON FLARES

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The active region McMath No. 9740, which produced many proton flares, passed over the solar disk during 22 October to 4 November, 1968. These proton flares were associated with SSC geomagnetic storms. During this period, the Pioneer 6 spacecraft was approaching the sun. Fig. 1 shows a projection of the position of this spacecraft on the plane perpendicular to the sun-earth line. The experiment of the polarization measurement for the 2,292 MHz radio wave transmitted by the spacecraft began on 26 October 1968 to investigate the electron density distribution near the sun (Stelzried et al., 1970). When this experiment started, this spacecraft was at a distance about  $17 R_{\odot}$  from the sun (Fig. 1), and the active region mentioned above was located in the region  $\sim 35$  degrees east on the southern hemisphere of the sun.

A proton flare occurred on 4 November just before the disappearance of this active region from the west limb and this flare produced a transient Faraday rotation phenomenon for this transmitted wave. When this phenomenon was observed, the position of the spacecraft was  $\sim 11 R_{\odot}$  apart from the sun (Fig. 1). Taking into account a magnetic bottle ejected by this flare, moving through the medium between the spacecraft and the earth, Schatten (1970) explained this phenomenon and estimated an average expanding speed of this bottle to be  $\sim 200 \text{ km sec}^{-1}$ .

This flare was accompanied by MeV protons, KeV electrons, radio bursts of spectral type II, III and IV, interplanetary shock wave and

SSC geomagnetic storm (Sakurai and Chao, 1973). Contrary to a conclusion of Schatten (1970), therefore, we can say that this was a major flare. It must be noted here that this major flare produced a magnetic bottle expanding with the speed of  $\sim 200 \text{ km sec}^{-1}$ . In the case of the 12 November flare, which occurred in the active region McMath No. 9754, Schatten (1970) also obtained that the expanding speed of an associated magnetic bottle was  $\sim 300 \text{ Km sec}^{-1}$ . Therefore, it seems reasonable to assume that the mean speed of such expanding magnetic bottles is a few hundred kilometers a second.

More than 10 proton flares were produced in the active region McMath No. 9740 during its passage over the solar disk. These proton flares are described in Table 1 and 2 with associated phenomena such as type IV bursts and SSC geomagnetic storms. Their characteristics are similar to each other. Therefore, it seems reasonable to assume that all of these flares ejected magnetic bottles similar to that for the flare of 4 November. However, we do not know the expanding speed for these bottles from flare regions except for the case of the 4 November flare.

Let us assume first that the expanding speed estimated by Schatten (1970) can be applied to the bottles ejected from the flares described in Table 1. If this is the case, the speed of these bottles must be  $\sim 200 - 300 \text{ Km sec}^{-1}$  in their expansion through the envelope of the sun. Using this assumption and the flare data in Table 1, we will examine an upper limit of the radial distance where these bottles cease to expand

or break after ejection by flares. In this analysis, the flares which occurred on the western hemisphere are only useful because Pioneer 6 was approaching the west side of the sun, as shown in Fig. 1. Assuming that these bottles were radically expanding by  $200\text{-}300 \text{ Km sec}^{-1}$ , we have estimated the positions at which they seemed to have met with the radio waves transmitted by the spacecraft into the direction of the earth (Fig. 2). In this figure, solid circles indicate the positions where the bottles seem to have met with the radio waves from the spacecraft. For example, this figure indicates that the radial line along the path of the bottle ejected by a flare at 2339 UT of 30 October met with the path of the radio waves from Pioneer 6 at the regions in a distance of  $23 R_{\odot}$  from the sun. This bottle, therefore, would have reached the region, indicated by a solid circle of 30 October, between 1530 and 2130 UT of the next day. This time range is shown in Table 1. In this table, the time intervals marked by asterisk (\*) cover the period in which the experiment of the polarization measurement was under way (Levy et al., 1969; Stelzried et al., 1970). In order to find out any evidence for the passage of magnetic bottles, we may use these five experimental records for the polarization measurement.

As mentioned before, we have observed only once the Faraday rotation phenomenon, which was associated with the flare of 4 November. When this rotation phenomenon was observed, the position of the spacecraft was  $\sim 11 R_{\odot}$  in the radial distance from the sun (see Fig. 2). For the

other four cases indicated in Table 1, we have never detected such rotation phenomena in the radio wave transmitted from the spacecraft. This result seems to suggest that the magnetic bottles such as proposed by Schatten (1970) did not reach the region through which this radio wave passed: that is, these bottles may have not expanded into the region beyond  $12 R_{\odot}$  from the sun. Moreover, we may consider another possibility that such bottles were broken before they reach the region around  $12-13 R_{\odot}$  from the sun. In this case, it seems likely that the bottles, constituted by sunspot magnetic field lines stretched out of the flare regions, are broken in the region just mentioned above, and, therefore, that the flare ejectae stripped out of these bottles are only ejected into interplanetary space.

If we do not take up the hypothesis that the expanding speed of these magnetic bottles was  $200-300 \text{ Km sec}^{-1}$  for these 5 cases, we may say that the observation of the Faraday rotation was a result of an accidental coincidence. Therefore, we had better consider whether or not the expanding speeds of magnetic bottles are largely variable from flare to flare. In considering this problem, we may confer the data for the speeds of the interplanetary shock waves associated with the flares described in Table 1, because these speeds give an information on the behavior of these waves in the solar envelope. The generation of these waves is closely related to the production of magnetic bottles in flares (e.g., Smerd and Dulk, 1971; Dulk, Altschuler and Smerd, 1971; Sakurai, 1973a; Sakurai and Chao, 1973).

Table 2 summarizes the transit times between the sun and the earth of the shock waves associated with the flares shown in Table 1. Their estimated speeds, shown in Table 2, seem to be useful to infer the dependence of shock speed on the longitude positions of associated flares. Fig. 3 shows that the mean speed of the shock waves depends on the flare positions on the sun. Therefore, this speed seems to depend on the direction of the shock wave propagation in interplanetary space, and, furthermore, this dependence seems to be associated with the non-uniform propagation of shock waves in this space (Sakurai, 1973b). Taking into account this systematic variation of the shock speed with the position of associated flares, it seems reasonable that the radially expanding speed of a magnetic bottle is not quite variable, but remains almost constant from event to event (Sakurai, 1973c). Hence, it seems probable that Schatten's hypothesis for the expanding speed of magnetic bottle is applied to all the flare events shown in Table 1.

If we can apply a model for the expansion of magnetic bottles with the speed of  $200\text{--}300 \text{ km sec}^{-1}$  in the solar envelope, we need to explain why the flare events shown by asterisk (\*) in Table 1 were not associated with magnetic bottles except for the 4 November event. As shown in Table 1, for the four events, the regions where the bottles met with the radio waves transmitted by the Pioneer 6 spacecraft were farther than  $11R_{\odot}$  in the radial direction from the sun. This suggests that the magnetic bottles did not reach anywhere beyond  $12R_{\odot}$  from the

sun: all these bottles may have decelerated and then stopped before they reached the region around  $12R_{\odot}$  from the sun. Otherwise, they may have been broken in the region around  $12R_{\odot}$  from the sun. This result predicts that, after ejection by flares, no magnetic bottle arrives at the vicinity of the earth. In order for the main phase of an SSC geomagnetic storm to be explained, therefore, an agent must be sought instead of considering a magnetic bottle itself. Such an agent may be a hot gas cloud ejected as a result of the break of expanding magnetic bottles in the solar envelope. In summary, we may say that a magnetic bottle ejected by a proton flare does not necessarily expand into the region farther than  $12R_{\odot}$  from the sun: this bottle may stop or be broken in the region around  $12R_{\odot}$  away from the sun.



## References

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Table 1      Solar flares and the estimated times and positions for  
flare-associated magnetic bottles to meet with the radio  
wave transmitted from Pioneer 6.

Solar Flare				Magnetic Bottle		
Day	Time (UT)	Position	Imp.		Time <sup>1)</sup>	Distance <sup>2)</sup>
Oct. 30	2339	S14W37	3B	Oct. 31	1530-2130*	23.0
31	2232	S15W49	2N	Nov. 1	1630-1900*	17.7
Nov. 1	0820	S17W47	2B	2	0100-0300	17.3
2	0601	S20W58	2N	2	2000-2100*	14.3
	0949	S14W66	2B	2	2200-2300*	13.0
4	0520	S15W90	2B	4	1530-1600*	11.0

1) This time indicates that which a flare-associated bottle meets with  
the radio wave from Pioneer 6.

2) The distance where a flare-associated bottle meets with the radio  
wave from Pioneer 6.

\* During these times, the measurement of the polarization for the radio  
wave transmitted by Pioneer 6 was under way.

Table 2      Transit times of shock waves between the sun and the earth

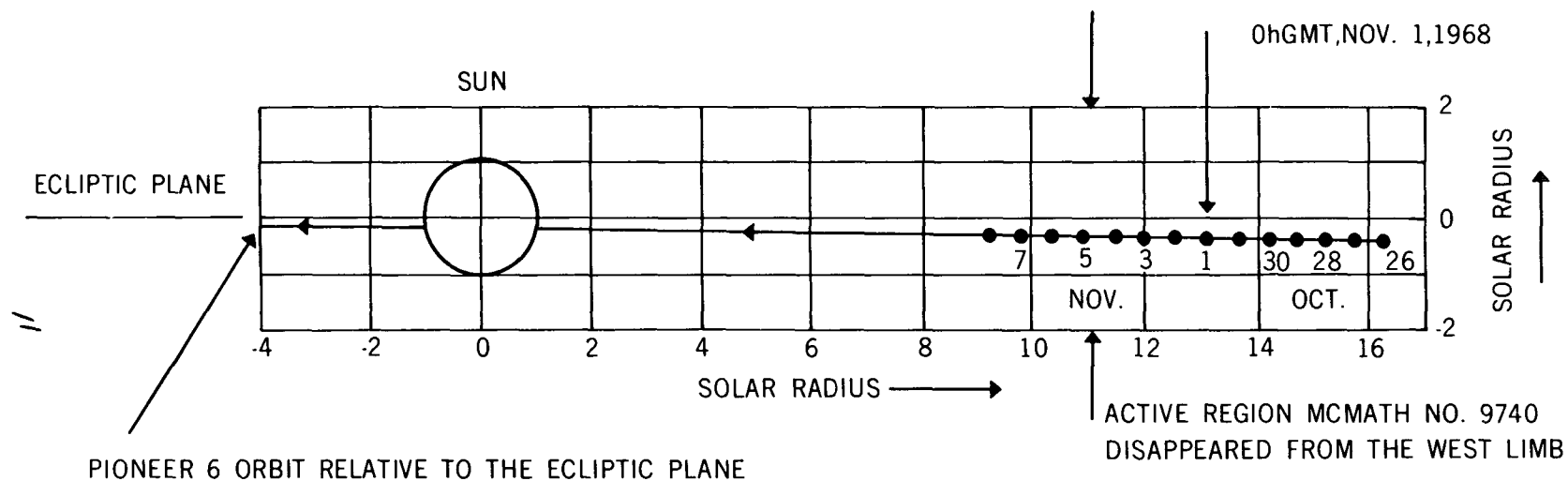
Day	Solar Flare Time (UT)	Position	Imp	Shock Wave Transit time (hrs)
Oct. 27	1235	S16E18	1B	----
	1318	S17E18	2N	> 50.5
29	1216	S16W12	1B	52
	1515	S14W19	(-N)	52
30	1334	S18W28	2N	48
	2339	S14W37	3B	46
31	2232	S15W49	2N	47
Nov. 1	0820	S17W47	2B	41
2	0601	S20W58	2N	52
	0949	S14W66	2B	51
4	0520	S15W90	2B	63

### Caption of Figures

Fig. 1. Projection of Pioneer 6 orbit relative to the plane of the ecliptic.

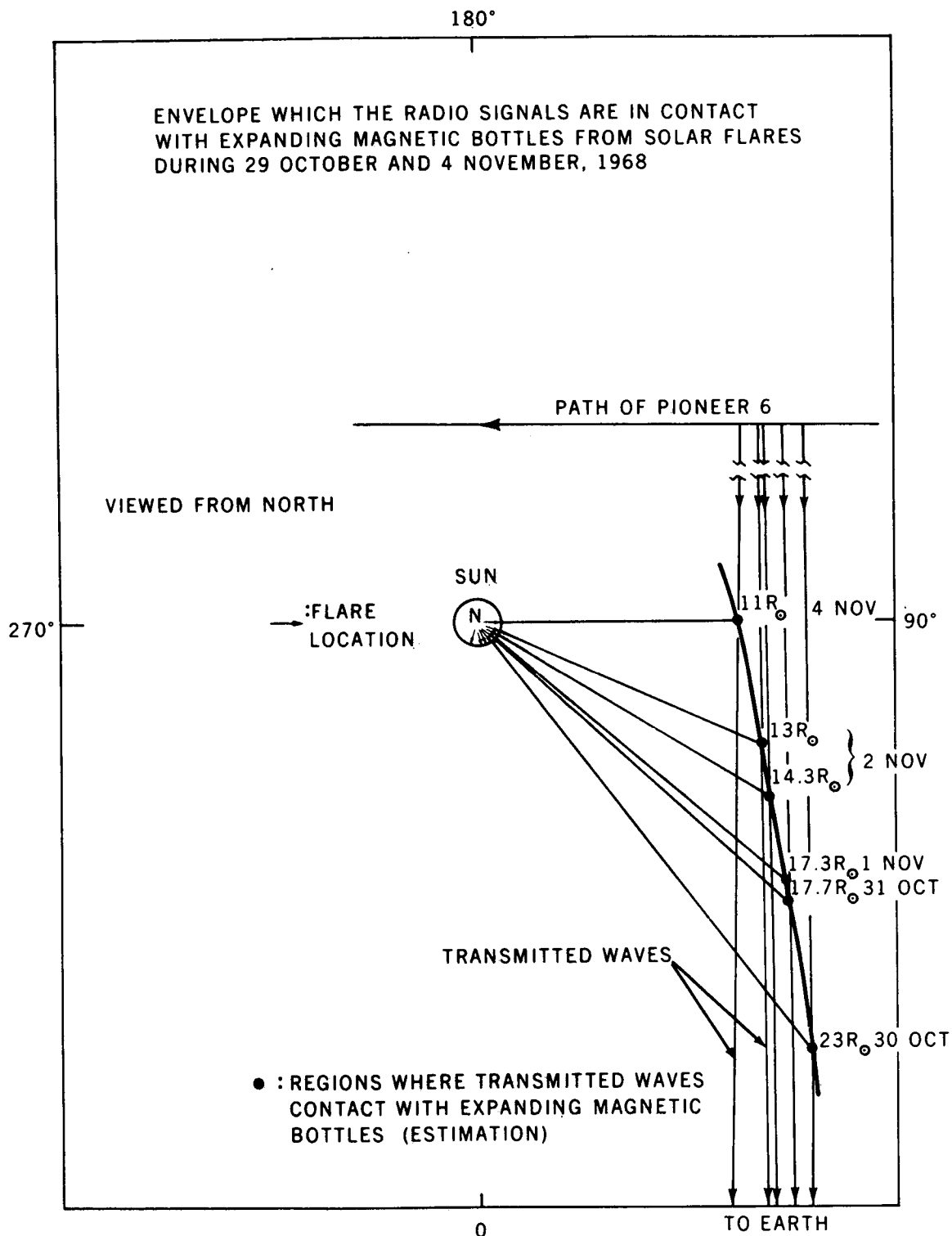
Fig. 2. The positions, where the radio waves transmitted by Pioneer 6 met with the expanding magnetic bottles with the speed of  $200-300 \text{ Km sec}^{-1}$ , are shown by solid circles. The distances in unit of the solar radius are shown with the days when associated flare occurred.

Fig. 2. The transit times from the sun to the earth of the shock waves associated with the flares shown in Table 1, as a function of the longitude position of these flares. This systematic variation suggests that the shape of the front remains constant for any flare shown in Table 1.



START OF EXPERIMENT OCT. 26, 1968

Fig. 1



12

Fig. 2

23 OCT.-7 NOV., 1968

